The Performance of the corDECT Voice/Data Wireless Local Loop

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Abstract

The traditional wired local loop used to connect each telephone subscriber to the nearest exchange is expensive and unreliable. Wireless Local Loop (WLL) systems largely eliminate these copper wires using wireless technologies and could provide a cost effective solution. corDECT is one such WLL system, based on the DECT (Digital Enhanced Cordless Telecommunications) standard, that provides toll-quality voice and data capability at a cost well below that of a wired local loop.

A closed Queueing Network Model (QNM) is proposed for the corDECT system. The model is validated against actual measurements. Our model predicts that the 1,000-line corDECT system would meet a Busy Hour Call Attempt (BHCA) of 36,000 calls/hr, which is far greater than its requirement of 20,000 calls/hr. The bottlenecks that limit the BHCA to 36,000 calls/hr were identified by the model. We show how the system could be expanded to a 10,000-line exchange with a BHCA of over 2,10,000 calls/hr. We also investigate the feasibility of implementing 64 kbps data service along with voice. It is shown that this requires modest hardware improvements.

Indexing terms: telecom; access network; performance model; mean value analysis.

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1. Introduction

Traditionally, a pair of copper wires is used to connect each telephone subscriber to the nearest exchange. Such a wired *local loop* poses the following problems [6]:

- The laying and maintenance of copper cable up to the subscriber's premises incurs high cost. The wired local loop contributes about one-third of the cost in providing a line to a subscriber. Also, this cost is increasing with time as the cost of copper increases.
- The per-line cost for rural areas is significantly higher due to the large amount of cabling infrastructure required to take even a few telephone lines to remote villages.
- Most faults are in the local loop, due to water-logging, damage or theft of cables.
- Rapid deployment is difficult owing to the regulatory and other problems in laying buried cables.

Wireless technology can provide a cost-effective solution to the local loop problems. The wireless service facilitates easy expansion of the network as installation is easier. Further, the cost of wireless technologies is primarily in electronics and is expected to come down with time. In order to be useful in urban areas of developing countries such as India, the wireless local loop technology must cater to high subscriber densities of 1,000–10,000 subscribers/sq.km. It must also provide toll-quality voice and data and FAX capability on par with a wired telephone.

1.1 The corDECT WLL System

One such wireless system is the corDECT Wireless Local Loop system (WLL) developed by the TeNeT Group of the Indian Institute of Technology, Madras, India; Midas Communication Technologies (Pvt.) Ltd, Madras, India and Analog Devices Inc., USA [1,3,5]. The corDECT system consists of four major subsystems as shown in Fig. 1.

DECT Interface Unit (DIU) **:** performs system control and interfaces to the Public Switched Telephone Network (PSTN).

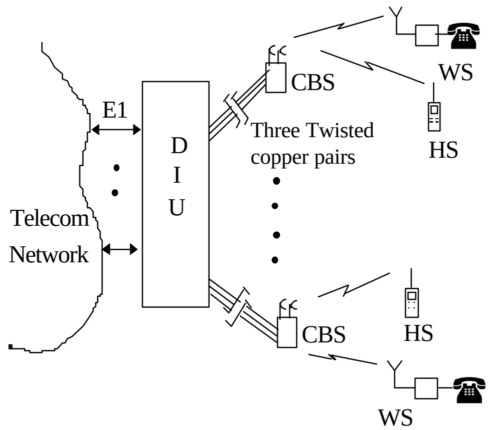

Fig. 1 1,000-line corDECT system architecture

Compact Base Station (CBS) : provides wireless access to subscribers in an area on twelve simultaneous channels.

Wallset (WS) : a wireless fixed terminal adaptor, with extended range, that can be connected to any standard telephone, modem or fax machine.

Handset (HS) : a portable telephone providing voice service to a user.

corDECT uses a micro-cellular architecture with a typical cell size of 50–300 m. This enables support for subscriber densities of up to 10,000 per sq. km [6]. It also has the advantage of good speech quality and a low transmit power of only 250 mW.

corDECT uses the DECT (Digital Enhanced Cordless Telecommunications) standard [11, 20] for communication between a portable* and CBS. DECT uses a variation of the Time Division Multiple Access (TDMA), the Multi-Carrier TDMA (MC-TDMA). The standard defines 24 time slots (termed *full slots*) so that up to 12 simultaneous calls can be handled (one full slot is used for receive and one for transmit). DECT divides its 20 MHz bandwidth into 10 frequency bands, hence a channel is a time-slot/frequency pair, resulting in 120 channels.

* In this paper we refer to *Handset/Wallset* as *portable*

Mobile cellular systems such as GSM use Fixed Channel Allocation (FCA) scheme (where each base station is allocated a set of frequencies for its use)[25]. This requires careful frequency planning and usually results in a monopoly operator in each area (city or even state). In DECT, on the other hand, the frequency is selected by the portable using Dynamic Channel Selection (DCS). The portable constantly monitor signals from various CBS around to switch to another CBS and channel if reception is better there. DCS provides for efficient bandwidth utilization, channel allocation based on the actual traffic interference situations and, most importantly, does not require frequency planning [3].

To be accepted by a service provider, the corDECT system must not only reduce the per-line cost but also meet the performance requirements laid down for a wired local loop system. Hence, it is important to analyse the performance characteristics of the corDECT system.

An approximate analytical model of the corDECT system which could fairly accurately predict the performance characteristics of the system is developed. The model is used to study the system capacity, to identify and improve the bottleneck subsystem, to examine the feasibility of expanding the capacity of the system and to investigate the feasibility of supporting data in addition to voice in the corDECT system.

1.2 Overview

Section 2 discusses the architecture and implementation aspects of the corDECT system. Section 3 presents the proposed Queuing Network Model (QNM). Section 4 validates the corDECT model against measurements in the corDECT system. In Section 5, we use the model to study the performance of the corDECT architecture. We conclude in Section 6 with a discussion of possible future work.

2. corDECT Architecture and Implementation

The DECT standard used by the corDECT system is designed for high density, micro-cellular systems that support voice telephony, high speed data, video and other multimedia applications [4]. The main features of the DECT standard are [15]:

- DCS, a process whereby the portable continuously scans all the channels and dynamically selects better channels when they become available.
- Roaming anywhere in the radio coverage network.
- Seamless bearer (or channel) handover from channel to channel or from cell to cell. This is transparent to the user even during a conversation.
- Authentication and encryption, which provide a high-level of security and privacy.

2.1 The DECT Protocol Stack

The DECT standard has been structured according to the Open Systems Interconnection (OSI) model [15]. DECT has defined four protocol layers for the air-interface. These correspond to the lower three layers of the OSI model. The functionality of these layers is discussed below:

Physical (PHL) Layer [21]

This layer specifies the radio frequencies and transmission characteristics, the division into 10 ms frames and subdivision of each frame into 24 slots. It monitors the quality of signal in all slot and frequencies used by the DECT equipment.

Medium Access Control (MAC) Layer [22]

This layer provides connections used for user data and some control, connectionless channels for control information flow and broadcast service to page a portable. It handles handover of a connection from one channel to the other due to link quality degradation (within a CBS), called *bearer handover*.

Data Link Control (DLC) Layer [23]

Using bearers provided by the MAC layer, the DLC layer creates and maintains reliable connections, provides connection-oriented and connection-less service to higher layer, handles handover of a connection at portable from one CBS to the other due to link quality degradation or CBS failure, called *connection handover*.

Network (NWK) Layer [24]

This layer establishes, maintains and releases calls (Call Control), handles mobility management, registration and authentication of portables. This layer along with MAC and DLC supports encryption of signalling, user voice/data information.

2.2 corDECT Architecture and Implementation

In wireless systems whose cell radius is very large, a single base station can serve subscribers in a city and hence it can even be located at the exchange. Serving a subscriber density of 10,000 subscribers/sq.km. requires a micro-cellular architecture with a cell radius of around 200 m [6]. Hence, many base stations distributed throughout are required to serve subscribers in a city. All these base stations cannot be located at the exchange. The local loop now consists of a wireless or a wired connection (employing N-ISDN, HDSL on copper cable) from the exchange to the base station and a wireless connection from the base station to the subscriber. The exchange is connected to the national network. Base stations would be mounted in posts, walls, roofs of buildings, etc.

The corDECT system employs a similar architecture as discussed above for a micro-cellular wireless system. The exchange here would be the DIU and it consists of a *OMC* (Operation and Maintenance Control), *SWITCH* (Voice/Data Path Switching subsystem) and *BIM*s (Base Station Interface Modules).

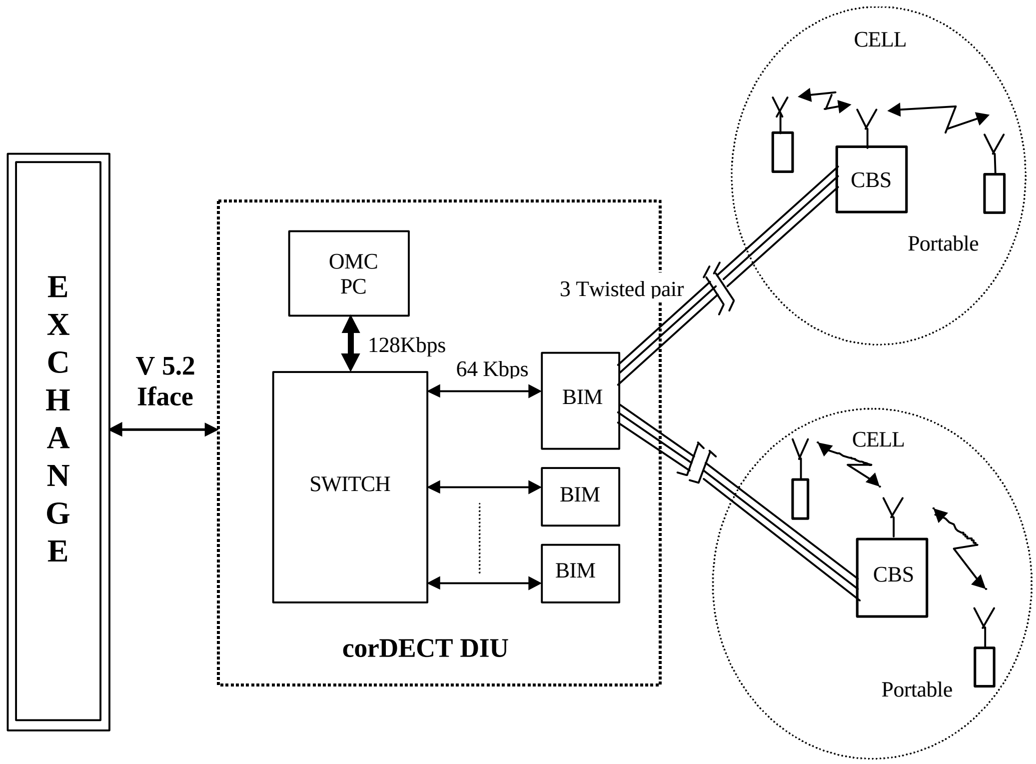

Fig. 2.2 corDECT 1000-line system architecture

Table 1 Some corDECT System Parameters

CPU at SWITCH, CBS and portable	ADSP 2181 at 33 MHz, 16K x 24-bit words Program Memory (PM), 16K x 16-bit words Data Memory (DM).
CPU at OMC	Pentium at 100 MHz, 16MB RAM
OMC-SWITCH link	128 kbps
SWITCH-BIM link	64 kbps
BIM-CBS link	16 kbps

The OMC is a standard Personal Computer (PC) running LINUX OS. The *OMC* performs call processing, and runs the DECT NWK Layer. The *OMC* provides user interface to the operator of the corDECT system, performs the system operation, maintenance, remote fault monitoring, subscriber registration and billing.

The *OMC* is connected to the *SWITCH* through a 128 kbps signalling link. The *SWITCH* is responsible for switching the voice between the subscribers and runs a part of the DECT DLC Layer viz., LAPC (Link Access Protocol for C-plane). All the base stations (called *Compact*

Base Station (*CBS*)), distributed across the region are connected to the DIU through three standard subscriber wires that may already be laid for Wired Local Loop. The link between the CBS and the DIU provides 16 kbps signalling bandwidth. The CBSs are connected to the DIU at the BIM and each BIM supports two CBS. The BIMs are connected to the SWITCH through 64 kbps signalling link. The SWITCH monitors the health of the BIMs and CBSs connected to them.

The CBS provides 12 duplex radio links supporting 12 simultaneous calls [3]. The CBS runs the other part of the DECT DLC Layer viz., Lc Layer (MAC layer interface), the entire DECT MAC and DECT PHL Layers. The *portable* runs the entire DECT protocol stack.

In addition to these layers, the Inter-Working Unit (IWU) layer that handles the user interface at the *portable* and at the *OMC* performs subscriber billing, registration, etc. and connect the DECT subscribers to the conventional Public Switched Telephone Network (PSTN) is implemented in the corDECT system.

2.3 Call Scenario

The call scenario of a portable A calling portable B, keeping the call active for sometime and then portable A releasing the call is shown in Fig. 3. It shows the sequence of events at the DECT DLC, the DECT NWK layer messages exchanged in this call scenario.

3. Performance Evaluation

3.1 Objectives

In this work, we study the performance of DIU and CBS of the corDECT system. An analytical model of the corDECT system that could fairly accurately predict the performance characteristics of the system is developed. The model is used to study the system capacity, to

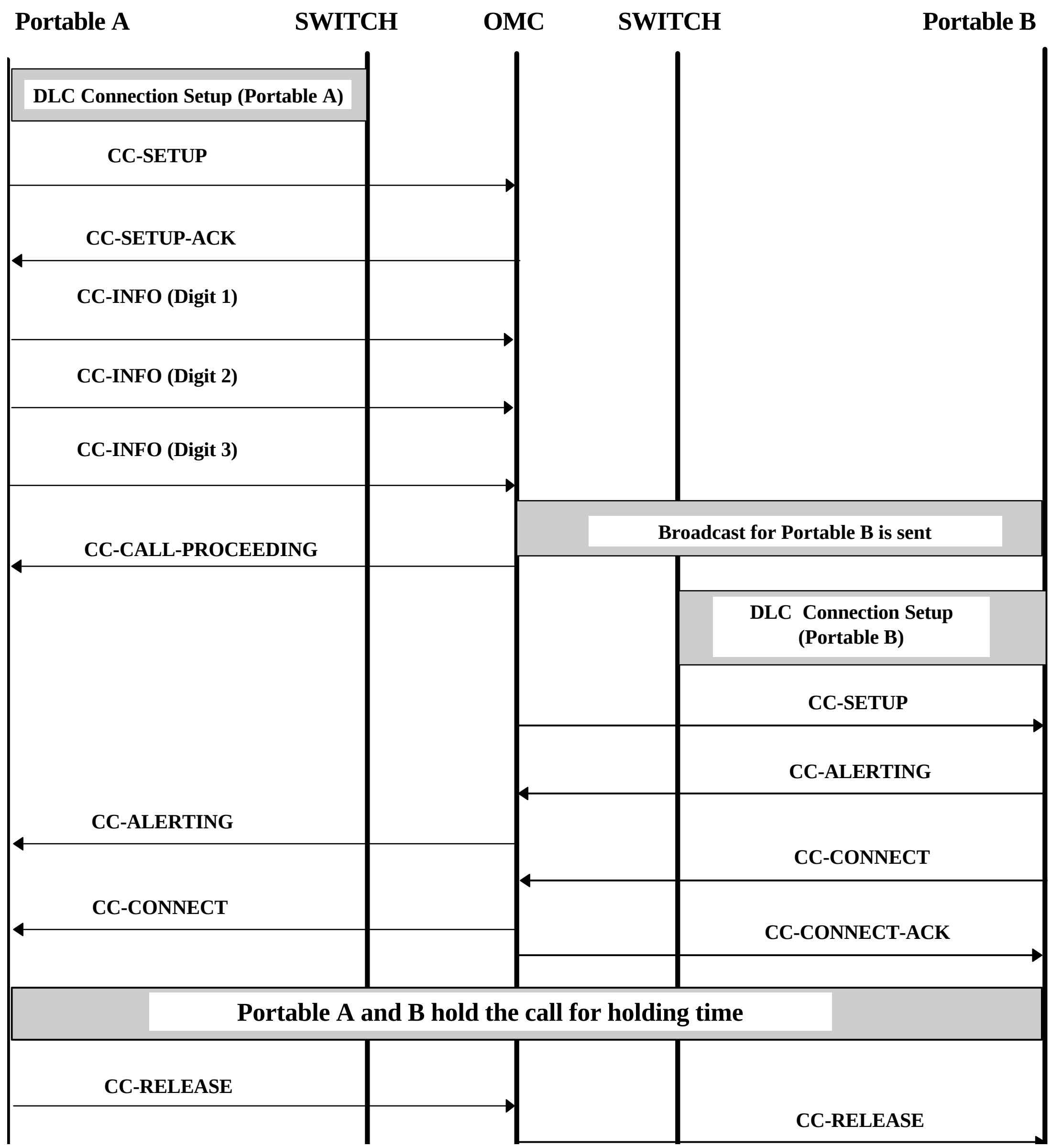

Fig. 3 Network Layer messages exchanged for one complete call

identify and improve the bottleneck subsystem, to examine the feasibility of expanding the capacity of the system and to investigate the feasibility of supporting data in addition to voice in the corDECT system.

3.2 The Model

Performance measurements with a large system such as a 1,000-line corDECT system is difficult. Hence, we develop a simple Queuing Network Model that can be efficiently used to study the corDECT Architecture. Mean Value Analysis (MVA) [12, 19] is an efficient solution technique for networks of queuing centres. The exact MVA technique is used to solve the corDECT Analytical model (Section 3.2.2).

3.2.1 Job Identification

We are interested in investigating the performance of the corDECT system with increasing number of calls. Hence, we define a *job* as a complete call between two subscribers. A call is initiated by a *calling subscriber*, the *called subscriber* answers the call. Here, *calling* and *called subscriber* form a portable *pair*. After the *call holding time* the *calling subscriber* releases the call. We study only one type of call i.e. a completed call, and hence have only one *job class* for the model. The sequence of *events* in a job is shown in Fig. 4.

In the call attempt, User A and B are valid subscribers with three digit subscriber number, B is free when A calls B and call loss due to non-availability of air slot is assumed negligible. The *call answering time* at B is 1 sec, while the *call holding time* and *time between subsequent calls (inter-call time)* can be varied. The system is analysed with maximum of four pairs of portable per CBS and DCS is not activated at the portable.

With the *job* and the performance objective being defined, we find that there will only be a *finite* number of jobs in the corDECT system. This type of system is best modelled as a closed Queueing Network Model (QNM) [12, 18, 27]. For this model, we use a non-executable, probabilistic, interactive type of *workload* [16].

3.2.2 Analytical Model

The proposed corDECT closed QNM is shown in Fig. 5. In this model, the *terminals* of the conventional closed QNM are the subscriber's portable attempting calls and have a *think time, Z.*

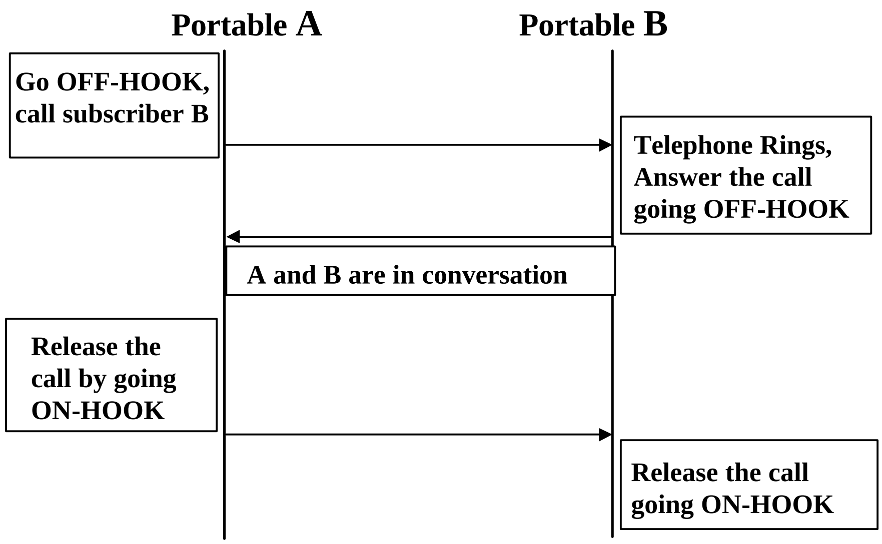

Fig. 4 Sequence of events in a *job*

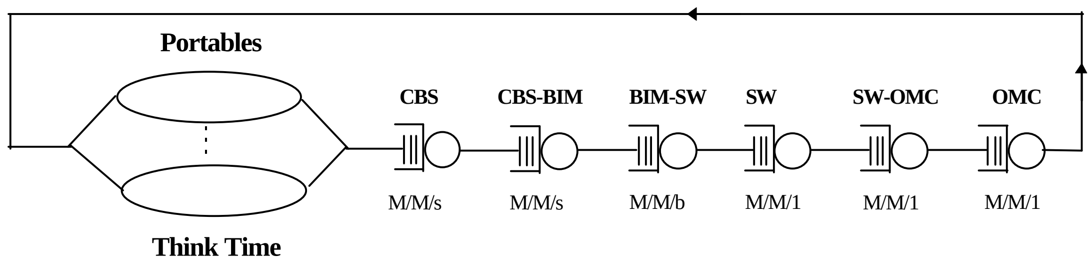

Fig. 5 corDECT closed QNM

A *portable* can select a free channel in any of the CBSs. Hence, the CBSs are modelled as M/M/*s* queue (where *s* is the total number of CBS in the system) with *service demand*[†] D_{CBS}. Since, two CBS are connected to a BIM, the BIM-SWITCH link is modelled as M/M/*b* queue, where $b = s/2$. It has a service demand $D_{BIM\text{-}SW}$. We need *s* links to connect CBSs and BIMs, hence CBS-BIM link is modelled as M/M/*s* queue having a service demand $D_{CBS\text{-}BIM}$. BIM is not involved in DECT call processing, hence, is not modelled as a separate server. We have a central SWITCH, OMC and a communication link connecting them. These three components are modelled as M/M/1 queue, and these servers have service demands D_{SW}, D_{OMC}, $D_{SW\text{-}OMC}$ respectively. The description of the service demands of the servers and the

[†] *Service Demand* is the average time taken for service of one job at the service centre.

measured service demands from the actual system are tabulated in Table 2.

4. Validation

Validation of a performance model involves comparing measured performance values with the performance values calculated by the model.

4.1 Validation Procedure

Using the measurements in the corDECT system (Section 4.3) we estimate the Mean Value Analysis (MVA) parameters (service demand at each server) for one job in the corDECT system. Given the demands in each server and the number of servers in the system, we solve the analytical model using the MVA algorithm and predict the performance parameters viz. response time, throughput and queue length for more than one job in the system.

Table 2 Service demands of the servers in the corDECT model

Symbol	Description	Measured Service Demand (ms)
D_{OMC}	Service demand at OMC server, for processing all messages of a call.	47.81
D_{SW}	Service demand at SWITCH server, for processing all messages of a call.	196.59
D_{CBS}	Service demand at CBS server, for processing all messages of a call.	15.49
Z	Think Time, the time taken for processing all messages of a call at portable + the time taken for transmitting/receiving these messages in air.	2884.34
$D_{SW\text{-}OMC}$	Service demand for transmitting/receiving all messages of a call in the link between SWITCH and OMC at 128 Kbps.	34.01
$D_{BIM\text{-}SW}$	Service demand for transmitting/receiving all messages of a call in the link between BIM and SWITCH at 64 Kbps.	136.63
$D_{CBS\text{-}BIM}$	Service demand for transmitting/receiving all messages of a call in the link between CBS and BIM at 16 Kbps.	533.85

4.2 Measurement Tools

A software probe module is added to the corDECT software without affecting its normal operation. This module is built in each subsystem of the corDECT system except OMC. This module provides functions to start and stop the probe timer. Using this timer, the time interval between the transmission of a request and reception of a response can be measured.

4.3 Estimating Service Demands

4.3.1 SWITCH service demand

We start a timer at the CBS when a request is generated and it is stopped when the response for the request arrives from the SWITCH. We accumulate this time interval for all requests and responses for a call. Let this time be T_{CBS}. We have,

$$T_{CBS} = D_{CBS\text{-}BIM} + D_{BIM\text{-}SW} + D_{SW} + D_{SW\text{-}OMC} + D_{OMC} \quad (4.1)$$

We use a similar timer at SWITCH for measurement. Let the total measured time for a call be T_{SW}. We have,

$$T_{SW} = D_{SW\text{-}OMC} + D_{OMC} \quad (4.2)$$

To obtain SWITCH service demand D_{SW}, (4.1) - (4.2) gives,

$$T_{CBS} - T_{SW} = D_{CBS\text{-}BIM} + D_{BIM\text{-}SW} + D_{SW} \quad (4.3)$$

The service demands at link servers namely, $D_{CBS\text{-}BIM}$, $D_{BIM\text{-}SW}$, $D_{SW\text{-}OMC}$ can be calculated from the given data rates and message length, and is a constant. Hence, the SWITCH service demand can be estimated as,

$$D_{SW} = T_{CBS} - T_{SW} - D_{CBS\text{-}BIM} - D_{BIM\text{-}SW} \quad (4.4)$$

4.3.2 OMC service demand

From (4.2), we calculate OMC service demand as,

$$D_{OMC} = T_{SW} - D_{SW\text{-}OMC} \quad (4.5)$$

4.3.3 CBS service demand

At CBS, we use additional timers to measure the processing time of all messages of a call. We measure the time interval between the time when a message arrives from SWITCH and the time when the message is transmitted on air. We also measure the time interval between the time when a message is received on air and the time when the message is transmitted to SWITCH. We sum up the time interval recorded for all messages of the call and we thus obtain $D_{CBS.}$

4.3.4 Think Time

Let the total time for a call measured at the portable be, T_P. Then,

$$T_P = Z + D_{CBS} + D_{CBS\text{-}BIM} + D_{BIM\text{-}SW} + D_{SW} + D_{SW\text{-}OMC} + D_{OMC} \qquad (4.6)$$

Since all the service demands are known, *think time* (Z) is calculated as,

$$Z = T_P - D_{CBS} - D_{CBS\text{-}BIM} - D_{BIM\text{-}SW} - D_{SW} - D_{SW\text{-}OMC} - D_{OMC} \qquad (4.7)$$

4.4 Validation Results

Table 3 gives a comparison of response time obtained from the measurement in the actual system and from the analytical model. The response time obtained from measurement is expressed as confidence interval with a confidence level of 95%. From Table 3, we observe that the error in the analytical model with respect to measurements is less than 10% almost always. There is a similar observation for varying call holding time and time between calls, when $N = 1$. Thus, the analytical model can be used to predict performance measure of the corDECT system with fairly good accuracy.

Table 3 Error in analytical model w.r.t measurement, confidence intervals at 95% confidence level shown for measurements (all times in ms)

N	**Measurement**	**Analytical**	**Error Range %**
1	2858 ± 9.7	2849	0.0–0.7
2	2884 ± 11.9	2939	1.4–2.3
3	2932 ± 17.1	3046	3.2–4.3
4	2988 ± 29.4	3175	5.0–6.8
5	2938 ± 15.5	2950	0.1–0.9
6	2957 ± 23.2	2992	0.4–1.9
7	3027 ± 30.7	3040	0.6–1.4
8	3078 ± 44.1	3097	0.8–2.0
9	3110 ± 66.0	2995	1.6–6.0
10	3154 ± 68.5	3028	1.8–6.4
11	3211 ± 73.8	3066	2.3–7.1
12	3293 ± 82.3	3109	3.3–8.6

5. Results

In this section, we use our validated analytical model to investigate the performance of the corDECT system and its enhancements. We first consider the corDECT system used only for voice (Section 5.1) and then study the performance with data traffic also (Section 5.2).

5.1 corDECT Voice Network

5.1.1 Busy Hour Call Attempt (BHCA)

Conventionally, the capacity of a telephone switching system is measured by the maximum number of call attempts per hour (during busy hour of the day) that can be handled by the system. This measure is referred to as BHCA.

The corDECT system is a 1,000-line exchange and is expected to meet a BHCA of 20,000 call attempts/hr. The BHCA experiment was conducted using portables programmed to automatically generate calls. A number of parameters such as the *time between calls* and *call holding time* could be varied.

In this experiment the *call answering time* was fixed at 1 sec, *call holding time* was fixed at

100 ms and *time between calls* at 1 second. With 15 pairs of portables generating calls the average response time for a *job* completion (i.e. complete call setup and release Section 3.2.1) including the time between calls was found to be 4.8 sec**.** Hence, the BHCA is,

= (1/4.8) × 3600 × 15 × 2 call attempts/hr

= 22,500 call attempts/hr

Note that, each complete call has two call attempts, one between the calling portable and DIU and the other between DIU and called portable.

In this experiment, there is no blocking. Hence, we can use the analytical model to predict BHCA. The average response time for a complete call predicted for 15 pairs of portables (*N*=15) including the time between calls is 4.2 sec**,** and the throughput obtained from the analytical model is 0.003574 call attempts/ms (Fig. 6). Hence, the BHCA is, 25,732 call attempts/hr. This error of 14 % compared to the measured value is acceptable.

5.1.2 Throughput

Fig. 6 shows the throughput characteristic of the system from analytical model for varying number of portable pairs, *N*, attempting calls simultaneously. From the throughput characteristic, we observe that at around *N* = 30 the graph saturates at a throughput of 0.005 call attempts/ms. Hence, the maximum BHCA that can be achieved is 36,000 call attempts/hr. The throughput of the system can be improved by identifying and improving the bottleneck server. The bottleneck server can be identified from the utilization graph (Fig. 7).

Corresponding to the throughput saturation, the utilization of SWITCH approaches 1.0 at around *N* = 30. Hence, this is the bottleneck server. The graph also shows that the next

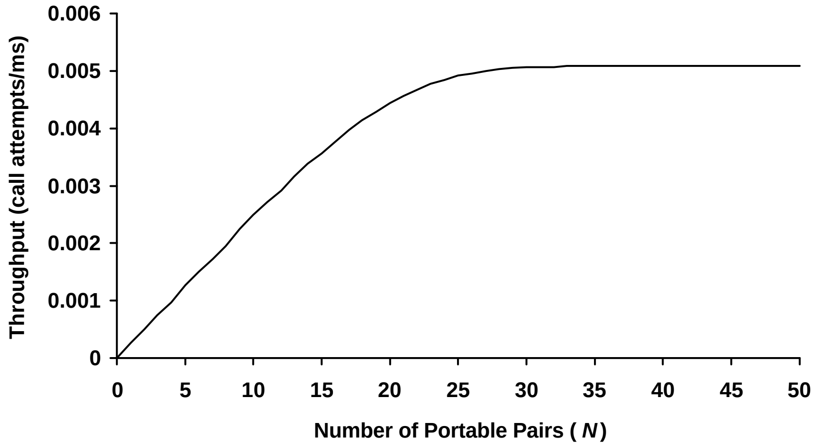

Fig. 6 System throughput characteristic from analytical model for varying *N*.
(At the Saturation Value, *N* = 30, Throughput = 0.005 call attempts/ms).

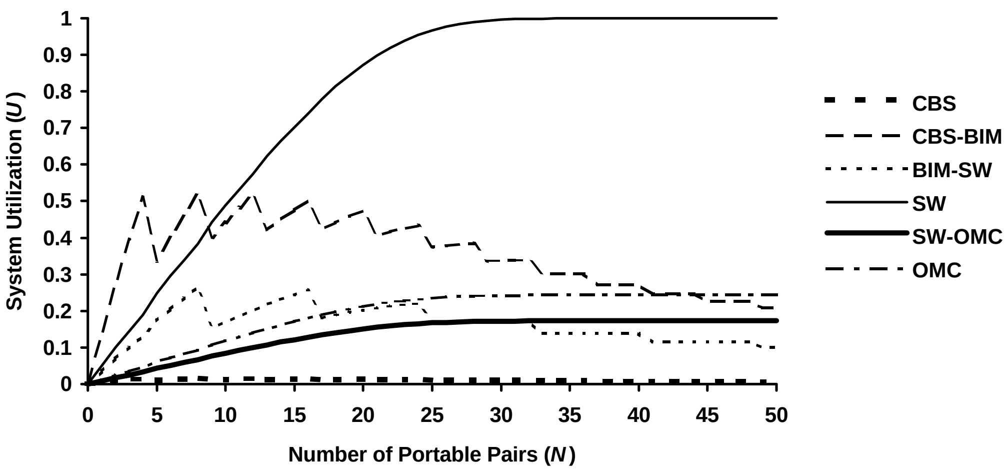

Fig. 7 System utilization characteristic from analytical model for all servers
in corDECT system for varying *N*.

bottleneck server is the OMC and the next is the CBS-BIM link, when the system is examined at *N* = 50. In the utilization graph, the utilization of the link servers namely, CBS, CBS-BIM and BIM-SWITCH exhibits two important characteristics namely, a saw-tooth behaviour and decrease in utilization as *N* increases.

In the corDECT model discussed in Section 3.2.2, the CBS and CBS-BIM link are modelled as multi-server M/M/*s* queues, where *s* is the number of CBS in the system. We analyse the system with four pairs of portables per CBS, adding a CBS for every four pairs of portables in the system ($s = (N + 4 - 1) / 4$). We observe an increase in utilization from $N = 1$ to 4 and then a decrease at $N = 5$, since, a new CBS is added at $N = 5$ but, there is only one portable pair corresponding to the new CBS. Thus, the new CBS and the corresponding CBS-BIM link are less utilized and we observe an overall decrease in the utilization characteristic. The utilization of these servers increases from $N = 5$ to 8, and then decreases at $N = 9$, and so on. Thus, we observe a saw-tooth behaviour in the CBS and CBS-BIM utilization characteristic.

The BIM-SWITCH link is modelled as an M/M/b queue, where $b = s/2$ i.e. one BIM is added for every two CBS in the system. Hence, we observe a similar saw tooth behaviour as in the CBS and CBS-BIM utilization characteristics, but at N multiples of 8.

As we add more CBSs to the system, the central components namely, SWITCH and OMC get overloaded and their utilization starts saturating at 1. Hence, beyond this saturation the utilization of CBS, CBS-BIM and BIM-SWITCH servers decreases as N increases. Thus, we observe an increase and then a continuous decrease in utilization of CBS, CBS-BIM and BIM-SWITCH link.

5.1.3 Improving Bottleneck Server

In the corDECT system, we identified SWITCH server as the bottleneck. We study two different ways of improving the server,

- Increasing the processing speed at SWITCH employing increased MIPS processor
- Shifting some percentage of the service demand from SWITCH to any other server

MIPS increase at SWITCH

From Fig. 8, using the analytical model we observe that as MIPS at SWITCH increases the values (N) at which the utilization of SWITCH saturates at 1 increases. At 165 MIPS, SWITCH server does not saturate at utilization of 1, hence, the SWITCH is no longer the bottleneck.

Fig. 9 shows that OMC also saturates at higher values of N as MIPS at SWITCH increases and it saturates at utilization of 1 for 165 MIPS of SWITCH processor, hence, OMC becomes the bottleneck.

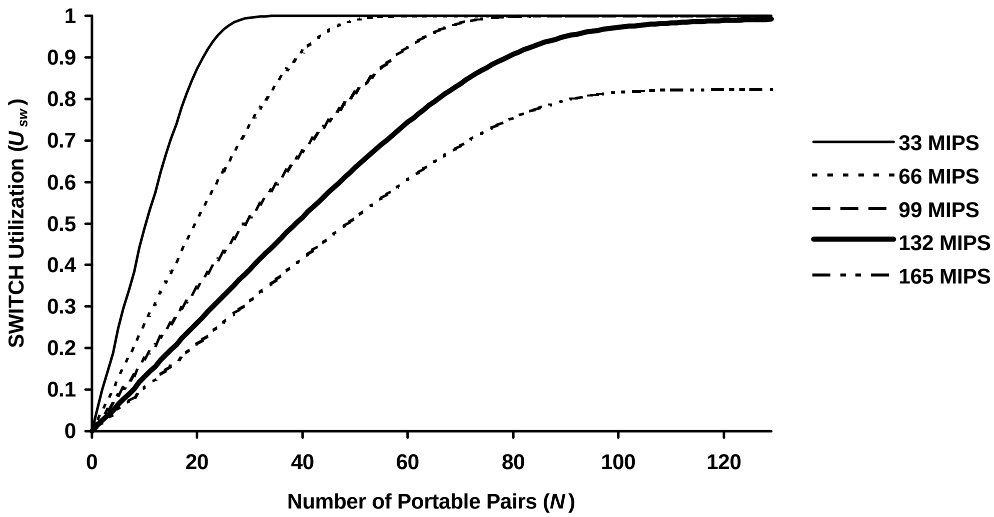

Fig. 8 Comparison of utilization characteristic for various MIPS at SWITCH server

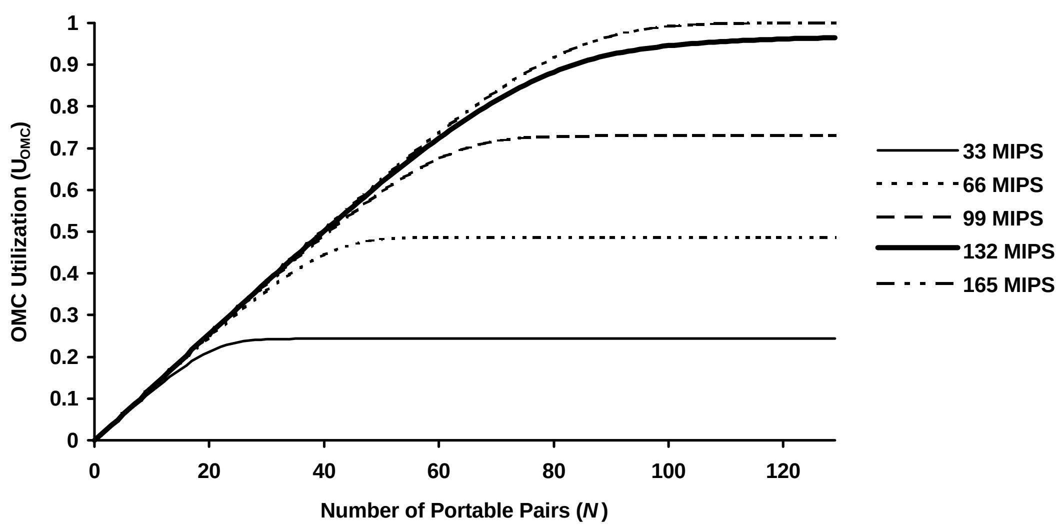

Fig. 9 Comparison of the utilization characteristic of OMC server
for varying MIPS at SWITCH server

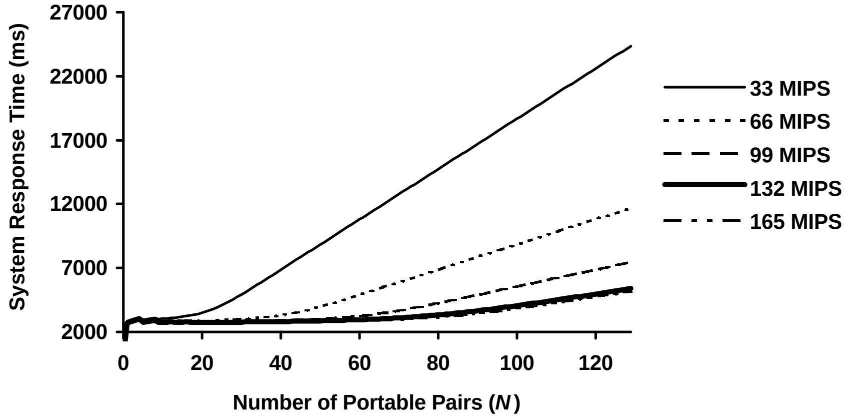

Fig. 10 Comparison of the response time characteristic of system
for varying MIPS at SWITCH server

In the response time graph (Fig. 10), the decrease in response time becomes lesser as SWITCH MIPS increases and there is virtually no decrease in response time between 132 and 165 MIPS.

From Fig. 11, we observe that the throughput saturates at almost the same value for 132 and 165 MIPS of SWITCH processor. This indicates that the system performance can no longer be improved by increasing SWITCH MIPS beyond 165. The next bottleneck server, namely, the OMC needs to be upgraded to improve the performance. The observed saturation values for varying MIPS at SWITCH are tabulated in Table 4.

Shifting Service Demand from SWITCH

The DLC Layer in the DECT protocol stack is split into two sub layers viz. LAPC (Link Access Protocol for Control plane) and Lc (Lower part of DLC). In the current configuration LAPC is implemented at SWITCH and Lc is implemented at CBS. The LAPC module broadly consists of two sub modules. One module allocates resources, maintains DLC connections, performs connection handover procedure. The other module forms and transmits DLC frames, runs the DLC window protocol in transmitting data between peer entities, handling time-outs and retransmission of DLC frames.

Table 4 BHCA values for varying MIPS power at SWITCH

MIPS	N_{max}	Throughput (calls/ms)	BHCA (call attempts/hr)	SWITCH utilization	OMC utilization
33	30	0.0050	36,000	0.98	0.24
66	52	0.0101	72,000	0.99	0.48
99	73	0.0151	1,08,720	0.99	0.72
132	111	0.0200	1,44,000	0.98	0.96
165	117	0.0209	1,50,480	0.82	0.99

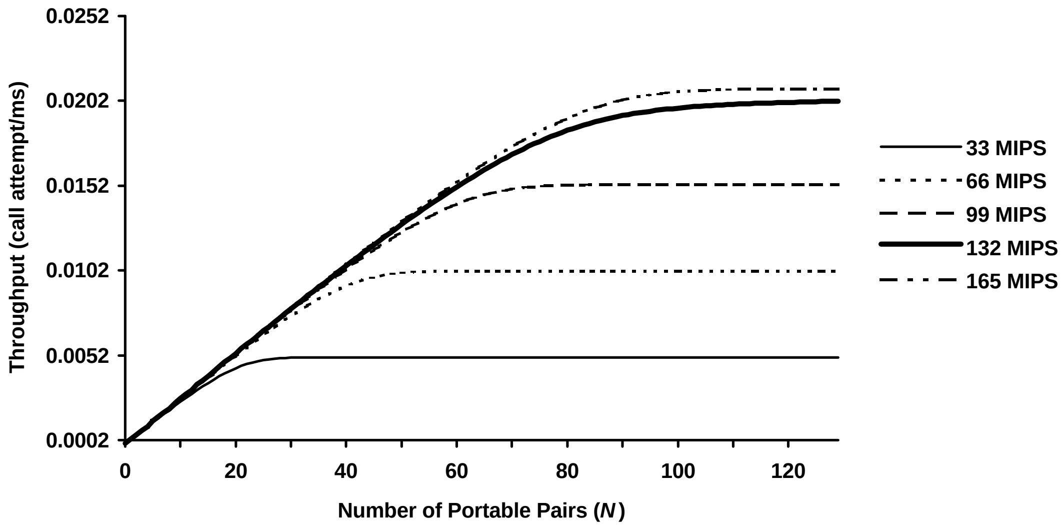

Fig. 11 Comparison of the throughput characteristic for various MIPS at SWITCH

The first module has to reside at SWITCH necessarily since connection handover and resource maintenance is best handled at a central place that can view and control all the CBS. The second module however can be implemented at the CBS or BIM. Since, CBS is already running the DECT MAC and Lc layers, we can implement this module at BIM. We study the possibility of shifting various percentages of service demand from SWITCH to BIM server using the analytical model. Investigating this scenario, we need to add BIM server to the model, and the modified model appears as in Fig. 12. The throughput characteristic of the system is shown in Fig. 13 for various percentage shifts of service demand from SWITCH to BIM. The throughput saturation values are tabulated in Table 5.

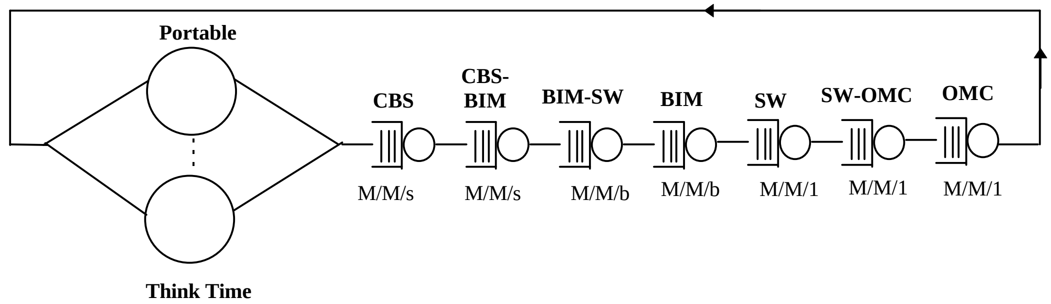

Fig. 12 Modified corDECT model

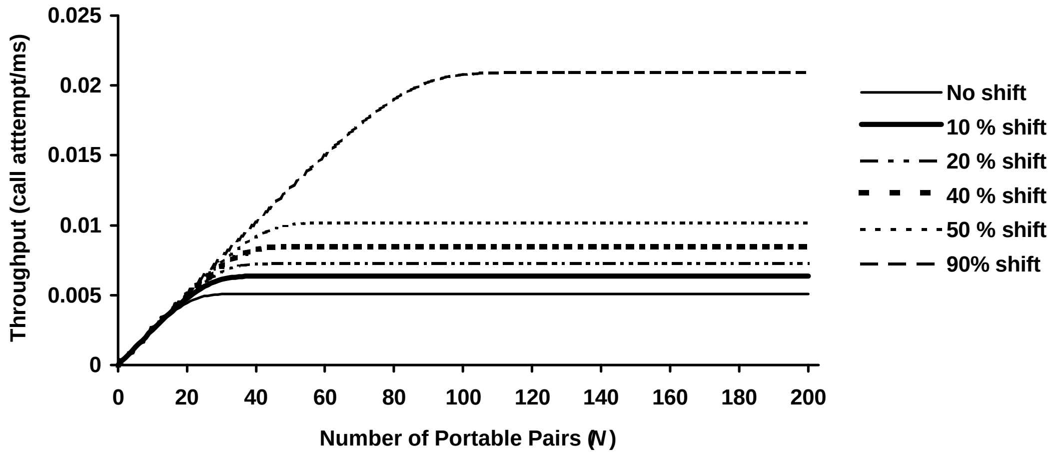

Fig. 13 Comparison of throughput characteristic for different percentage of shift of SWITCH server demand to BIM server

Table 5 BHCA for varying shift in SWITCH service demand

%Shift	**Throughput (calls/ms)**	N_{max}	**SWITCH utilization**	**OMC utilization**	**BHCA (call attempts/hr)**
0	0.0050	30	0.99	0.24	36,000
10	0.0056	33	0.99	0.26	40,320
20	0.0063	35	0.99	0.30	45,360
30	0.0072	39	0.99	0.34	51,840
40	0.0084	44	0.99	0.40	60,480
50	0.0101	53	0.99	0.48	72,720
90	0.0209	109	0.41	0.99	1,50,480

5.1.4 Different CBS Configurations

Owing to vendor requirements, the corDECT CBS may be configured with 1 to 4 CBSs per BIM. We find that there is no significant difference in the throughput among the above system configuration. The response time and utilization (at the SWITCH) also show no significant difference for these configurations.

5.1.5 corDECT as a 10,000-line Exchange

The corDECT system currently supports 1,000 lines. If the corDECT system is to be redesigned for supporting 10,000 lines, we can estimate the requirements of the system from the analytical model.

For a 1,000-line exchange we achieved a BHCA of 20,000 call attempts/hr (Section 5.1.3). In a similar proportion, a 10,000-line exchange has to achieve 2,00,000 call attempts/hr. We use the study of improving the bottleneck server (Section 5.1.3) for analysing the feasibility. We investigate here one possibility of improving the capacity of the corDECT system, assuming no faster processor is available. We introduce the following changes in the current corDECT system,

- Shift 90% of SWITCH processing from SWITCH to BIM
- Increase the speed at SWITCH server by employing two 33 MIPS processors (assuming a communication overhead of 10% in the service demand).
- Upgrade the OMC, which currently uses a 100 MHz Pentium processor to 166 MHz.
- Upgrade the switching matrix in the SWITCH subsystem to a 5120 × 5120 matrix from the existing 512 × 512.
- DIU is upgraded to support 100 BIMs.

The analytical model is solved for the above system and the result is tabulated in Table 6. We observe that these changes would result in a system with acceptable BHCA.

Table 6 Performance measures for corDECT 10,000-line configuration

N_{max}	Throughput (calls/ms)	SWITCH utilization	SW-OMC link utilization	OMC utilization	BHCA (call attempts/hr)
155	0.02939	0.289	1.0	0.846	2,11,608

5.2 corDECT Data Network (Wireless LAN)

Wireless LANs provide flexibility and services to users who cannot be well served by the traditional wired LAN [26], and can extend or even be used as a substitute for a wired LAN.

A system that can offer both wireless speech and data services over the same infrastructure may provide extremely flexible and cost effective solutions to users. The users of wireless LANs would be organizations that [13],

- need local terminal mobility and the ability to flexibly re-configure their LAN,
- require a temporary LAN,
- are situated in buildings where the installation of extra cabling is costly, disruptive or forbidden

Today, Internet access is becoming increasingly important. In corDECT, the local loop upto the subscriber unit is digital. Hence the system could offer both wireless speech and data services over the same infrastructure in an extremely flexible and cost effective manner.

5.2.1 DECT Support for DATA Service

A range of DECT Data Service Profiles (DSPs) [13] has been developed to permit efficient use of the DECT radio resources for data transmission purposes, and to provide throughput data rates of up to 552 kbps. The DECT DSPs make use of the powerful mechanisms for data transmission provided by the DECT Common Interface (CI) standard [20-24]. Compared to modern solutions using a voice channel, the DECT DSPs, exploit the full capabilities of the DECT CI standard that provides, high throughput, lower bit error rate, better reliability, improved spectrum usage and better battery economy. In systems complying with the Generic Access Profile (GAP), ETS 300 444 [14], the integrated voice/data system may be implemented efficiently.

The DECT standard defines two planes of operation, the Control plane (C-plane) used for signalling information transfer and the User plane (U-plane) used for transfer of user voice/data. Although U-plane services are defined for DECT DLC and MAC layers. We discuss here, only the U-plane services at the DLC layer. The DECT DLC Layer [23] defines different types of U-plane service, referred to as LUx service. The U-plane services currently defined are,

LU1 Transparent Unprotected service: used for applications that do not need processing of U-plane data e.g. speech and this service is currently supported in the corDECT system.

LU2 Frame Relay service.

LU3 Frame Switch service.

LU4 Forward Error Correction (FEC) service

LU5 Basic Rate AdapTion (BRAT) service: no FEC, but provides reliable delivery of data packets through the Automatic Retransmission Requests (ARQ) protocol. It provides transparent transport of synchronous data at 8, 16, 32, 64 kbps/s data rates.

LU6 Secondary Rate AdapTion (SRAT) service: operates in conjunction with the LU5 service and enables rate adapt data terminal equipment with V-series interfaces to be interfaced to one of the input rates provided by the LU5 service.

LU7 64 kbps data bearer service.

LU16 Escape service: allows for implementation-specific U-plane protocol.

Akerberg [10] concludes that DECT-based WLL systems are suitable for POTS (Plain Old Telephone Service), general ISDN services, Internet and other packet data services. The DECT MAC layer provides several alternatives for data [10, 22]:

a) A full-slot duplex bearer carrying *unprotected 32 kbps ADPCM.* This full-slot provides telephony speech quality for bit error rates, BER, 10^{-3} on the air interface. The 32 kbps ADPCM channel supports transparent voice modem services up to 4.8–9.6 kbps when the transmission on the air interface is essentially error free.

b) A double-slot duplex bearer carrying *protected transparent 64 kbps PCM.* The protection service is LU7, which adds ARQ and Forward Error Correction (FEC) to the unprotected 80 kbps double-slot. This ensures BER < 10^{-8} for the PCM service when BER ≤ 10^{-3} on the air interface. Thus 28.8 kbps transparent modem services, V.34 and unrestricted 64 kbps ISDN services are supported for BER ≤ 10^{-3} on the air interface.

c) A full-slot bearer carrying 24 kbps *protected packet data* with BER < 10^{-8} when BER ≤ 10^{-3} on the air interface.

The corDECT system currently supports the bearer service defined in (a). To support data we need a protected service. We currently plan to provide 64 kbps protected service, defined in (b). Hence, we investigate the LU7 service in detail.

5.2.2 Modelling LU7 Service

Voice band modem data rates over unprotected 32 kbps ADPCM may be as low as 1.2 or 2.4 kbps at BER 10^{-3}, depending on the error distribution. This property is not DECT related, but typical for all radio technologies using the *unprotected 32 kbps* ADPCM coding, including CT2, PHS and PACS. Of these standards only DECT provides a *protected (LU7) 64 kbps bearer service* as required for ISDN and V.34 modem services [10]. The LU7 service is an immediate requirement for the corDECT system in supporting ISDN services at the portable. The requirements for the LU7 service and service demand estimates at various layers are discussed in the following sections.

Physical Layer

The LU7 service requires that the physical layer support *double slot* operation as against the *full slot* operation used for unprotected 32 kbps voice service [23]. Each *double slot* occupies two *full slots* and hence there can only be a maximum of six simultaneous data calls through a CBS.

MAC Layer

At the MAC layer, the U-plane/B-field requires the support for duplex unprotected normal delay service and is currently supported. It also requires, the support for advanced MAC connection set-up, full format page message, B-field signalling and B-field offering a data rate of 80 kbps [22, 23]. These features have to be newly added to the corDECT system. It is estimated that the LU7 service requirements for the PHL and MAC layers in supporting the services above, do not increase the service demand at any server significantly.

DLC Layer

At the DLC Layer, the service requirement can be broadly specified as [23],

- Forward Error Correction (FEC) using Reed-Solomon (R-S) coding
- Automatic-Repeat-Request (ARQ) algorithm
- Computation and Verification of checksum on data packets

The DECT DLC U-plane frame format for the LU7 service is shown in Fig. 14. The *Control field* is used by the ARQ procedure. The *Information field* carries the user data. The *Checksum field* carries the checksum computed on the control and information fields. The *R-S field* holds the parity symbol information for FEC.

The LU7 service at the DLC layer, is best implemented at the CBS since transporting 80 kbps U-plane data across to SWITCH would require changes in the corDECT architecture. Also, LU7 tasks done at a central subsystem (e.g. SWITCH) would require more processing power.

Control Field (2 bytes)
Information Field (90 bytes)
Checksum Field (2 bytes)
R-S parity symbol Field (6 bytes)

Fig. 14 DECT DLC LU7 packet format

FEC computation

It is estimated that the FEC algorithm would require at most 5 MIPS of the CPU for a data call from DIU to portable [7]. For a complete call from a portable to another portable 10 MIPS of CPU is consumed. Hence, for a 33 MIPS ADSP 2181 CPU it occupies 30% of the CPU.

ARQ procedure

At the DLC Layer, well-defined Automatic-Repeat-Request (ARQ) procedures and the checksum ensure reliable delivery of data packets. A window protocol with a window size of 8 is defined. In addition to the sequence number, all packets have a checksum. Packets that have checksum errors are stored and marked as error but not delivered to the higher layer for a fixed duration. If an error-free packet is received with the same sequence number as the packet in error then the stored packet (in error) is overwritten by the error-free packet. If an error-free packet is not received within the fixed duration the packet received in error is delivered to the higher layer. All packets sent to the peer entity are acknowledged and if no acknowledgement is received within a fixed duration the packet is retransmitted.

A data packet is received every 10 ms and processing needs to be done on this packet. The ARQ procedures used for LU7 service is almost similar to the ARQ procedures defined for the Control plane (C-plane) at the DLC layer. Hence, from the knowledge of current implementation it is estimated that the ARQ algorithm would require about 700 instructions on ADSP 2181 processor to process one LU7 frame.

Checksum computation

The checksum algorithm used in LU7 service is almost similar to the MAC Layer A-Field (which carries the C-plane information at the MAC layer) CRC algorithm. In the current implementation the algorithm for x 16-bit words require, $13 \times x + 10$ instructions in ADSP 2181 processor. The checksum in the LU7 service is computed over the 720 bits of information field, 16 bits of control field and a 16-bit constant.

Number of bits on which checksum is computed = 720 + 16 + 16 = 752 bits

Number of 16 bit words = 752/16 = 47 words

Hence, number of instructions needed to compute checksum,

$= 13 \times 47 + 10 = 621$ instructions ≈ 700 instructions.

Table 7 summarises the number of instructions needed for one data call from DIU to portable.

Table 7 Instruction requirement for one data call from DIU to portable
(in one direction only)

Task	No of instructions
LU7 ARQ	700
Checksum	700
Total	1400

Table 8 CPU occupancy for a complete data call

Task	CPU occupancy
FEC	30 %
ARQ and Checksum	2 %
Total	32 %

Assuming symmetric processing (for receiving and transmitting a frame),

Total number of instructions to process one LU7 frame = $1400 \times 2 = 2800$ instructions

On a 33 MIPS ADSP 2181 processor, this would consume approximately 100 μs of processing for every 10 ms data packet reception. Hence, 1% of the CPU is consumed for this processing. For a complete call 2% CPU would be consumed. Hence, the total CBS CPU consumption for implementing FEC and ARQ algorithm in software is shown in Table 8.

5.2.3 Inflating Service Demand in Modelling the LU7 Service

The QNM developed for the corDECT voice network can be extended to model data network by inflating the service demand at the CBS [12], to include additional processing due to LU7 (data) calls. In this section, we derive a formula to get the inflated service demand due to data calls. Let,

T = DECT frame time, time interval in which data packets are received.

t = CPU time at CBS for one data call from portable to DIU (in one direction).

n_{avg} = Average number of data calls through a CBS

n =Total number of data calls in the entire system

The utilization of a CBS CPU due to n_{avg} calls through the CBS is given by,

$$U_{AVG} = n_{avg}\ t/T \tag{5.1}$$

(out of of T time units, $n_{avg}t$ time units are used by the data call).

Let,

D_{CBS} = the service demand of the CBS multi-server queue due to signalling traffic.

$D'_{CBS}(N)$ = the inflated service demand at a CBS for signalling traffic when there are a total of N complete data calls in the system.

N = Total number of complete data calls.

For a complete call, two data call between portable to DIU are required (i.e. called portable to DIU and then from DIU to calling portable). Hence,

$$N = n / 2 \tag{5.2}$$

In Section 3.2.2, we have seen that multiple CBS in the corDECT system is analytically modelled as a multi-server M/M/s queue, where s is the total number of CBS in the system. From queueing theory [17], for x jobs at the CBS, its service demand is given by,

D_{CBS} = x x Avg. service demand at a CBS, if $0 \le x \le s$, else (5.3)

s x Avg. service demand at a CBS, if $s \le x$

Average service demand at a CBS for signalling traffic (D_{AVG}) = D_{CBS}/s (5.4)

The inflated service demand (due to data calls) can be derived as,

$$D'_{CBS}(N) = D_{AVG} \text{ x } (1 / (1 - U_{AVG})) \tag{5.5}$$

$n_{avg} = n/s$ (5.6)

Substituting Equations (5.2) and (5.6) in Equation (5.1), we have,

$U_{AVG} = (2 \text{ x } N / s) \text{ x } (t/T)$ (5.7)

Substituting Equations (5.4) and (5.7) and in Equation (5.5), we have,

$D'_{CBS}(N) = D_{CBS} / [\text{s x } (1 - ((2 \text{ x } N / s) \text{ x } (t/T)))]$ (5.8)

Reed-Solomon FEC in Software

In Section 5.2.2, we estimated that 32% of CPU would be occupied by one data call if all the LU7 tasks were done in software. In this case, we find that three complete calls are possible through a CBS (which is the maximum number of calls possible through a CBS). The inflated service demand can be derived as,

$D'_{CBS}(N) = D_{CBS} / [\text{s} \times (1 - ((N/s) \times 0.32))]$ (5.9)

With maximum number of calls through the CBS, the CPU would be utilized to a maximum of 96% for data calls, and CPU may not be left with enough processing power to do other tasks like communicating with BIM, communication on air, etc. This CPU consumption severely affects the performance of the CBS and hence the corDECT system. Hence, the FEC algorithm has to be implemented in a separate DSP or a dedicated hardware to achieve better performance.

Reed-Solomon FEC in a Separate DSP or a Hardware Module

The Reed-Solomon FEC algorithm if done in a separate DSP or a hardware module, then the service demand due to data calls would be the ARQ and checksum processing alone, which consumes 100 µs processing.

Substituting, t = 100 µs and T = 10 ms (DECT frame time) in Equation (5.8),

$D'_{CBS}(N) = D_{CBS} / [\text{s x } (1 - ((N/s) \text{ x } 0.02))]$ (5.10)

Substituting this inflated service demand in the original corDECT analytical model, various performance parameters can be calculated.

6. Summary and Conclusions

The corDECT system and the subsystems that affect the performance were examined and an analytical model of the system was developed. The analytical model was validated using measurements in the actual system. The error was found to be less than 10 % almost always. Hence the model can be used to predict performance measures of the corDECT system fairly accurately.

Using this model the corDECT system is predicted to exceed the BHCA requirement of 20,000 calls/hr. This result was verified in the actual system during the Telecommunication Engineering Centre (TEC), India, validation of the corDECT system. The SWITCH subsystem was identified as the bottleneck. To improve the system performance, using the analytical model we studied the effect of increasing the processor MIPS at SWITCH, and shifting part of the protocol processing from SWITCH to BIM. We found that with a 165 MIPS SWITCH processor, the SWITCH is no longer the bottleneck, and OMC becomes the bottleneck. Based on this study we found that the corDECT architecture could be extended to a 10,000 line exchange by several relatively modest changes such as increasing processor MIPS and reassigning of protocol processing (Section 5.1.3).

The corDECT system was examined for feasibility of data support using the analytical model of the system. We found that LU7 64 kbps data service can be implemented without significantly affecting the performance, provided Forward Error Correction (FEC) algorithm using Reed-Solomon coding is performed using a separate DSP or hardware (Section 5.2).

6.1 Future Work

The model does not consider the effect of bearer or connection handover and mobility management procedures and could be refined to study the effect of these on the performance of the system. The model does not consider call blocking at the air interface. It could be modified as a blocking closed QNM to study the blocking probability of calls in the system. The model considers only one type of call. It can be modified to consider a mix of different types of calls. Currently, the paging strategy used at the network layer is to broadcast the identity of the portable to all CBS in the DIU. This strategy increases the traffic significantly and hence can be improved using the methods discussed in [9]. The improved strategy can be studied by refining the model.

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